P148278.PDF [Page: 3 of 10]

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Radar Tracking in Multipath: Techniques for Improved Performance

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Summary

The low–elevation tracking performance of naval fire–control radars may be degraded by specular multipath. Performance can be significantly improved provided the radar has sufficient frequency agility and the appropriate signal processing is used. This paper examines the performance of a number of alternative techniques: monopulse averaged over a group frequencies within the agile band, monopulse with averaging weighted according to the signal–to–noise ratio and the use of a detailed propagation model in a maximum likelihood estimation technique called the Refined Maximum Likelihood (RML) method. Simulation results are presented to show that moderate improvement can be obtained by using monopulse with frequency averaging with a better improvement given by weighted averaging, the degree of improvement increasing with agile bandwidth. Where very precise height tracking of targets in a specular multipath is required, the RML technique is best. While RML was originally developed for antenna array signal processing, it can be applied to the two sub antennas of a phase monopulse system provided a sufficient degree of frequency agility is available. In this latter application, the technique has been designated RMONO for Refined monopulse. The basis of the RML technique is presented followed by an evaluation of its performance using results obtained from two experimental trials.

1. Introduction

Radar tracking of low–altitude targets over the sea is problematical; the reflection from the sea surface causes large errors in monopulse trackers. A number of techniques, e.g. [1,2] have attempted to improve the performance of monopulse tracking with less than satisfactory results. The development of high resolution signal–processing techniques such as the eigen–vector based MUSIC [3] at first seemed to offer the possibility of resolving the direct path signal from the interfering sea reflection. The MUSIC techniques failed to solve the problem because of the very high degree of correlation between the direct and reflected signals. As well, MUSIC is primarily for array signal processing; most radar systems do not have the multiple receiver array systems required.

Maximum Likelihood Estimation (MLE)has been proposed as a solution to the multipath problem. MLE can be formulated as an array signal–processing technique and applied to angle–of–arrival estimation [4,5,6,7]. There have been many attempts to apply MLE to direction finding under various names. Ballance and Jaffer [8] have analyzed a number of apparently different techniques and shown that they are equivalent implementations of MLE. References [5,6] specifically address the problem of sea reflection and tracking radars.

MLE is a model–fitting approach; in the case of Gaussian probability density functions, the likelihood function is maximized by adjusting the model parameters to obtain a least–squares fit to the data–vector outputs of an antenna array. It has been shown that the choice of model has a large effect on the ability of MLE to alleviate the multipath problem for tracking radars. The implementations of the MLE cited in [4–7] use the Angle–Of–Arrival (AOA) model. Here each signal is represented as having an unknown angle–of–arrival and an unknown amplitude and phase. Each of the unknown parameters must be explicitly or implicitly estimated. Specular multipath is represented as two such signals: a direct path signal and a signal reflected from the sea. If the radar has frequency agility, the number of unknowns is increased. In the radar context, the amplitude and phase of each signal changes with frequency. Therefore specular multipath is represented by two unknown angles of arrival and two amplitudes and phases per frequency. For N frequencies, the AOA model represents specular multipath with 4N+2 unknown parameters. In deriving the objective function to be maximized, the unknown amplitude and phases are eliminated mathematically; this leaves an objective function with two unknown parameters, the two unknown angles of arrival. A two–dimensional search is required to find the maximum of the likelihood function. Alternatively, a gradient technique can be incorporated into the algorithm for non–frequency agile radars [7]. The AOA model uses a minimum of a priori information: only the number of signals in the model must be specified in advance. Turner and Bossé [9,10] have developed algorithms based on a more detailed model of specular multipath employing a considerable amount of a priori information. The resulting angle–estimation technique is called the Refined Maximum Likelihood (RML) technique. The RML technique makes use of prior knowledge of the target range, the radar height above the sea and the sea state. Specular multipath is modeled by combining geometrical considerations with a priori information to obtain a signal model having a reduced number of unknowns in comparison with the AOA model: target height and an unknown amplitude and phase for each transmitted frequency in a frequency agile radar. For N agile frequencies, the RML model has 2N + 1 unknown parameters to be estimated, exactly half the number of unknown parameters in the the AOA model. For this reason, RML produces lower variance estimates and provides a significantly greater resolution capability than obtainable using the AOA model.

Wide–band frequency agility can be exploited to produce improved performance for many angle estimation techniques including the RML algorithm, MLE formulated with the AOA model for multiple frequencies and ordinary monopulse. Provided the required tracking precision is not too high, averaging over several monopulse estimates for a number of frequencies can produce a useful improvement in the tracking accuracy of monopulse systems. This can be particularly effective for reducing peak monopulse errors associated with nulls caused by destructive interference between the direct and reflected signals.

Following the introduction, this paper describes how elevation monopulse is affected by multipath for single frequency operation. The effectiveness of frequency agility for reduction of multipath errors is described; both simple averaging and weighted averaging are investigated. The basis of the RML technique is briefly described followed by

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P148278.PDF [Page: 4 of 10]

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an analysis of performance based on experimental results.

RML is an array signal processing technique. However, it can be applied to the two–element arrays typical of phase monopulse systems. In this special case, we use the name RMONO to designate the algorithm. RMONO can be applied to the two halves of an antenna that feed into an ordinary monopulse system; provided the radar has sufficient frequency agility, good results can be obtained. The paper will compare the performance of RML, RMONO and phase monopulse for a wide–band array system operating at X–band.

2. Effect of Specular Multipath on Monopulse

Fig. 1a illustrates the problem of tracking a sea–skimming target in the presence of specular multipath. The radar beamwidth is so broad that it is impossible to separate the target and its image. Monopulse systems are designed to detect the direction of arrival of a single plane wave incident on the antenna. The arrival of two closely spaced plane waves can cause large errors dependent on the relative phase difference between the two signals. Fig. 1b illustrates the view of an observer at the missile; the radar antenna and its image produce the illustrated lobing pattern. Exploitation of the high–resolution capabilities of the radar and its image will be later described in the context of the Refined Maximum Likelihood (RML) technique.

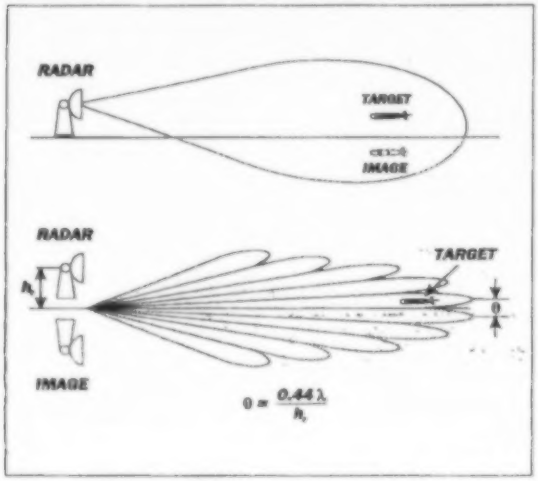

Figure 1 Effects of multipath on low–angle tracking

Monopulse is commonly implemented in two forms: amplitude monopulse and phase monopulse and in two dimensions: azimuth and elevation angle. A three–dimensional radar with amplitude monopulse may have three beamforming networks or feeds: a sum beam with a maximum in the direction of search; an azimuth difference beam which forms the difference between the outputs of two horizontally displaced sub antennas and an elevation difference beamform which is the difference between the outputs of two vertically displaced sub antennas. The difference beams have nulls in the direction of the sum beam. A calibration curve is obtained by determining the ratio of the outputs of the difference and sum beams. The measured ratio is then compared to the calibration curve to determine the angular distance of a target from the sum beam centre. Phase monopulse is implemented by measuring the phase difference between the outputs of the two sub antennas which can be related directly to angular position of the target with respect to the sum beam direction. Specular multipath affects both amplitude and phase monopulse in the same way: the null of difference pattern of the calibration curve is shifted in the case of amplitude monopulse; for phase monopulse a phase error is created. In both cases the angular error is the same. Therefore we evaluate the errors caused by phase monopulse in terms of the erroneous phase shift caused by multipath.

A phase monopulse system can be viewed as a two–element interferometer where the ambiguous grating lobes are suppressed by the directive pattern of the two sub antennas. These two sub antennas have apertures that are at least half the size of the total aperture; in the case of a reflector antenna the sub antennas may overlap and have an aperture virtually the same size as the reflector. A plane wave incident on the antenna at an angle θ with respect to the antenna bore sight gives rise to a phase difference , $\Delta\phi$, between the outputs of the sub antennas:

$$\Delta\phi = (2\pi d_c / \lambda) \sin\theta + \phi_m \qquad (1)$$

where d_c is the distance between the phase centres of the two antennas and λ is the wavelength. The quantity, ϕ_m, is an error term representing the effects of specular multipath which occurs whenever there is significant reflection from the sea and the two phase centres are at different heights above the sea. This effect is most severe in elevation monopulse systems; azimuth monopulse may also be affected but to a lesser extent when the radar antenna is not mechanically stabilized and the ship is subject to pitch and roll.

If we designate the signal outputs of the two sub antennas as S_1 and S_2, then θ is estimated as

$$\hat{\theta} = \sin^{-1}\left\{ \frac{\lambda}{2\pi d_c} \angle\left[\frac{S_1 \, |S_2|}{|S_1| \, S_2} \right] \right\} = \theta + \epsilon_m \qquad (2)$$

where ϵ_m is an error resulting from the combined effects of receiver noise which corrupts the measurement of S_1 and S_2 and the erroneous phase term, ϕ_m, resulting from multipath.

The effects of specular multipath on elevation monopulse are demonstrated by simulations. The antenna simulated is that used to obtain the experimental results reported in Section 6: a 32–element linear array of 1.82m length oriented in the vertical direction. Simulations are carried out for targets flying at fixed heights above the sea and with a constant unvarying receiver–noise level. This noise level is set to give a specified free–space signal–to–noise ratio on each of the the sub antenna outputs at a specified distance. As the target approaches, the signal strength increases as the inverse fourth power of range. The antenna bore sight is steered directly towards the target at all times during the simulation so that $\theta = 0$ in (2) and the resulting estimate is just ϵ_m, the error resulting from multipath and noise. It is this error, ϵ_m, that is plotted as a function of target range in the results to be presented.

The simulation results of Fig.2 shows the large angular errors caused by multipath in the elevation monopulse of a 1.82 meter 32–element linear antenna operating at 10 GHz in sea state 2 conditions. The upper sixteen elements are summed to form one input to the phase monopulse system while the bottom sixteen are summed to form the second input. For this simulation, the centre of this antenna is 20m above the sea surface and the target is moving towards the radar at a fixed height of 10m above the sea with a free–space signal–to–noise ratio of 20 dB at a range of 20 km at the output of each subarray. The target passes through different conditions of multipath with peak tracking errors corresponding to conditions where the null of the multipath interference pattern falls on the centre of the antenna. These errors become smaller as the sea surface roughens.

New active phased–array radar systems are being developed with solid–state Transmit/Receive (TR) modules. These radars support very wide–band frequency

P148278.PDF [Page: 5 of 10]

agility which allows a reduction in monopulse errors. Simulation results will be presented for agile bandwidths typical of these solid–state TR modules.

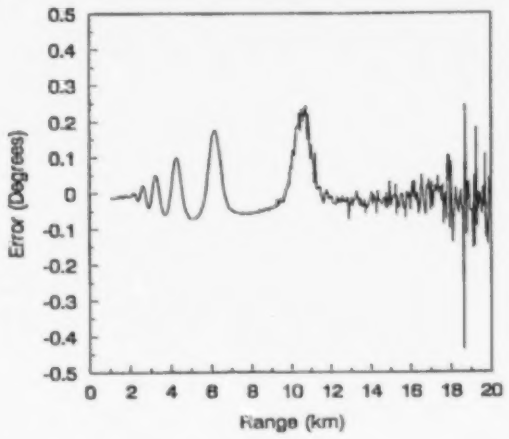

Figure 2 Monopulse multipath errors – single frequency

The simulation conditions are the same as those of Fig.2 except that different bandwidths and different processing methods are considered. Fig.3 shows the effects of averaging five angle estimates obtained by applying (3) to the sub antenna outputs, S_{1n} and S_{2n} for n = 1 to N = 5 frequencies evenly spread between 8 and 12 Ghz. The estimated angular position is

$$\hat{\theta} = \frac{1}{N}\sum_{n=1}^{N}\hat{\theta}_n$$

$$= \frac{1}{N}\sum_{n=1}^{N}\sin^{-1}\left\{\frac{\lambda_n}{2\pi d_c}\angle\left[\frac{S_{1n}\,|S_{2n}|}{|S_{1n}|\,S_{2n}}\right]\right\} \qquad (3)$$

where the symbol $\angle(\cdot)$ means the phase angle of the complex quantity within the brackets. A very substantial reduction in monopulse error is evident. A still greater improvement can be obtained by weighted averaging. Here the estimate for the nth frequency is given a weight proportional to the signal power $P_n = |S_{1n}|^2 + |S_{2n}|^2$. In this case, the estimated angular position is

$$\hat{\theta} = \left[\sum_{n=1}^{N} P_n\,\hat{\theta}_n\right] / \left[\sum_{n=1}^{N} P_n\right] \qquad (4)$$

The weighting operation in (4) de–emphasizes estimates obtained for frequencies which have strong fading; this causes a further reduction in errors as shown in Fig.4. Because the simulations are designed to always bore sight the antenna on the target as it flies towards the radar ($\hat{\theta} = 0$), equations (3) and (4) give the error resulting from a combination of multipath and noise.

Figures 5 and 6 show the corresponding performance for an agile bandwidth of only 2 GHz. The errors are greater in Figures 5 and 6 than in Figures 3 and 4 because of the reduced bandwidth. These results show that wide–band frequency agility can be used to reduce multipath errors. Note also that, although weighted averaging produces a much smoother error curve than unweighted averaging, a bias error continues to be present. The reduction in error obtained by using either weighted or unweighted averaging may be sufficient for semi–active defensive missile systems provided the radar has sufficient agile bandwidth. Gun systems and defensive missile systems employing command–guidance could benefit from more accurate

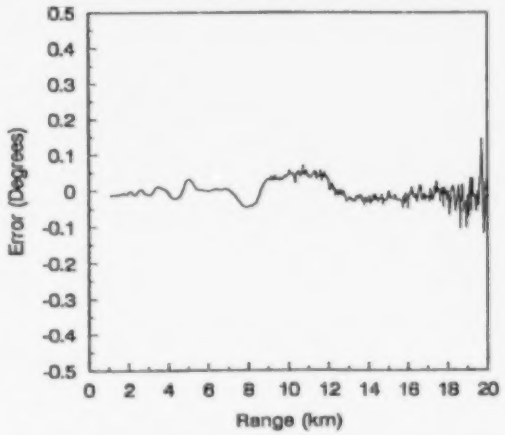

Figure 3 Monopulse multipath errors with simple averaging over 5 frequencies, 4 GHZ bandwidth

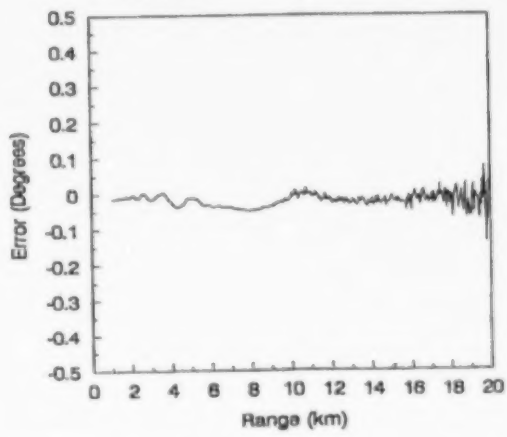

Figure 4 Monopulse multipath errors with weighted averaging over 5 frequencies, 4 GHZ bandwidth

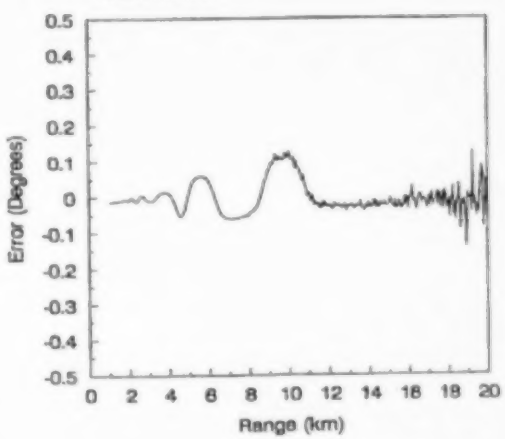

Figure 5 Monopulse multipath errors with simple averaging over 5 frequencies, 2 GHZ bandwidth

P148278.PDF [Page: 6 of 10]

tracking. Very accurate tracking can be achieved by using the Refined Maximum Likelihood (RML) technique to be described in the following section.

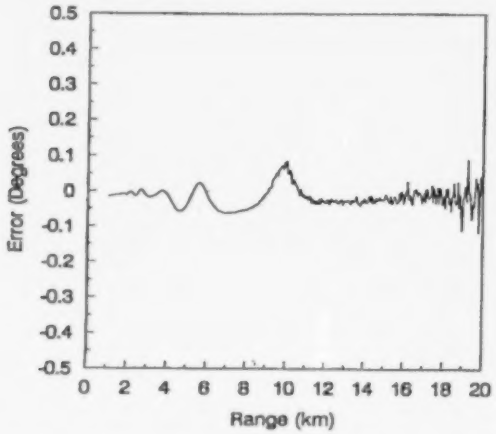

Figure 6 Monopulse multipath errors with weighted averaging over 5 frequencies, 2 GHZ bandwidth

3. The RML Technique

The RML technique is a near optimal procedure for estimating target elevation angle in specular multipath. The RML technique will be presented in the context of an array signal processing algorithm. It will then be shown that provided the radar has a large enough frequency agile bandwidth, the antenna array can be as small as two elements or sub arrays, ie, equivalent to phase monopulse. In this case we call the technique Refined Monopulse or RMONO. RML makes use of a priori information: target range, radar height above the sea and sea state. This information is combined with geometric considerations using small angle approximations as shown in Fig.7 to obtain a mathematical description of the variation of the multipath interference pattern over an array as

$$\mathbf{s} = b\mathbf{f}(h) + \mathbf{n} \tag{5}$$

where $\mathbf{s}$ is a column vector with kth component describing the received signal on the kth element of a vertically oriented array. The vector $\mathbf{n}$ describes the receiver noise on the array while $\mathbf{f}(h)$ describes the modeled specular multipath having only one unknown, the target height, h, above the sea. The complex quantity, b, represents the unknown amplitude and phase of the radar signal. Using the geometrical considerations illustrated in Fig. 7, the kth component of $\mathbf{f}(h)$ can be derived as in [10]

$$f_k(h) = \exp\{-j\xi(z_k^2 + h_k^2)/2R\}$$
$$\times [\exp(j\xi h_k z_k/R + A\exp(-j\xi h_k z_k/R)] \tag{6}$$

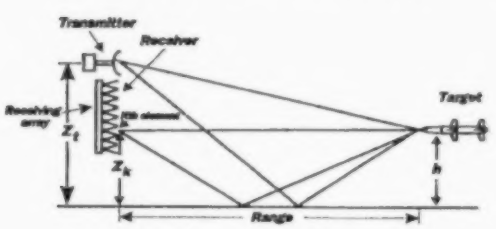

Figure 7 Geometry for multipath modeling

with $\xi = 2\pi/\lambda$ and where λ is the wavelength, z_k the height of the kth element, and R is the target range. The quantity A represents the complex amplitude of the reflected array as compared with the direct ray. A is determined from the reflection and specular scattering coefficients and the divergence factor [11]. Polarization enters the model via the reflection coefficient. All quantities are corrected for earth curvature. These corrections are different for each element height; hence the target height as viewed from the kth element is a function of k, indicated as h_k. Note that tracking radars always give the target range, R, with very good accuracy. Hence R is easily obtained with sufficient accuracy as an input to the model. The model also demands prior knowledge of the radar antenna height above the sea. Fortunately, the radar height need not be known with enormous precision. An accuracy of about one metre for a radar height of about 15 m [10] is sufficient for good performance .

A maximum likelihood estimate of the target height is obtained by maximizing the likelihood function, Probability $(\mathbf{s} - b\mathbf{f}(h))$, over the unknown parameters b and h. For a frequency agile radar having M frequencies, the likelihood function can be expressed as

$$L(h) = \prod_{m=1}^{M} P_m(\mathbf{s}_m - b_m\mathbf{f}_m(h)) \tag{7}$$

where $P_m(x)$ is a zero–mean Gaussian probability density function, with variance σ_m^2. The quantity σ_m^2 is related to the receiver noise vector in the mth frequency band as $E|\mathbf{n}_m|^2 = 2K\sigma_m^2$, where K is the number of array elements and the dimension of the vectors $\mathbf{s}_m$ and $\mathbf{f}_m(h)$. Here the index m indicates the mth frequency. The radar amplitude b_m fluctuates according to the Swerling models which comprise the probability density function for amplitude. Under the Swerling assumption, the phase of the b_m can be considered as uniformly distributed and independent from one frequency to the next. The likelihood function can be maximized taking account of the Swerling probability distributions or we can consider the b_m to be independent and unknown parameters to be estimated. A complete treatment of the Swerling models has been given in [10] where it was shown that only a minor performance difference is observed if the b_m are estimated as unknown parameters. This is also the simplest case to analyze and leads to a simpler formulation of the signal processing algorithm which follows.

$$C(h) = \frac{1}{\left(\sum_{m=1}^{M} |s_m|^2/\sigma_m^2\right)} \sum_{m=1}^{M} \frac{|\mathbf{s}_m^H \mathbf{f}_m(h)|^2}{\sigma^2 |\mathbf{f}_m(h)|^2} \tag{8}$$

As shown in [9,10], the likelihood function is maximized by choosing the target height, h, that maximizes C(h) in (8). It is instructive to examine the form of C(h) for a reasonable degree of frequency agility, for example, four frequencies spread over 10 to 12 GHz. The multiple lobes of C(h) shown in Fig. 8 correspond to the lobing structure of Fig.1b caused by the antenna and its image. This gives physical insight on why higher resolution is obtained by using the RML technique: the a priori information included in the model has allowed the exploitation of the inherent resolution of the interferometer pair made up of the antenna and its image. The use of frequency agility allows the resolution of the ambiguous lobes so that the largest lobe is the maximum of the likelihood function and indicates the true target height.

4. Experimental evaluation of performance.

Extensive evaluations of the RML technique have been carried out using both simulations and experiments[12,13]. Here we present results from two experiment: a dual frequency (8.6–9.6 GHz) radar experiment, the Project '90 trials at Sylt Germany, carried out under the auspices of AC/243 Panel III RSG.8; and a wideband beacon

P148278.PDF [Page: 7 of 10]

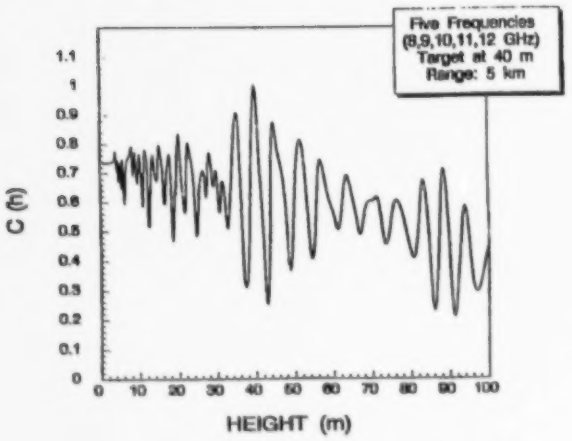

Figure 8 Likelihood function for RML technique

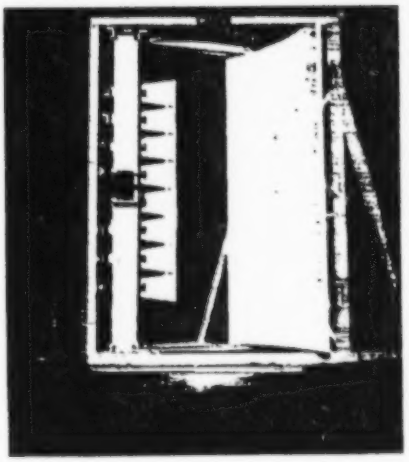

Figure 9 ELAT sampled aperture antenna system

experiment. The Sylt experiment provides a degree of realism beyond that of the usual beacon experiments. The radar had to cope with the usual problems of clutter and the detection of a low elevation target in a variety of sea conditions including some very rough conditions. The range of frequencies was, however, very limited.. In this case targets were corner reflectors mounted on poles driven into the sea floor. In contrast, the beacon experiment was considerably less realistic. The target was simulated by a fixed cw beacon; therefore clutter was absent and the SNR was very high. However, the bandwidth was typical of the very wideband capabilities of modern solid–state radars. The two experiments are therefore complementary, the first demonstrating that the RML technique works under conditions typical of real radar systems, the second demonstrating what might be achieved with very wide band radar systems.

5. The Sylt Experiment

This experiment was carried out as part of NATO Project '90 between September 10 and October 3, 1990 at Sylt Germany. Here we describe only the Canadian portion of this experiment which used an Experimental Low–Angle Tracking (ELAT) array radar system. The ELAT radar system has dual magnetrons and transmits two interleaved frequencies, 8.6 and 9.6 GHZ. The radar is "coherent–on–receive"; therefore coherent integration can be used to reduce the amount of data, eliminate clutter and achieve a high signal–to–noise ratio (SNR). The effect of varying levels of SNR can be determined by varying the amount of coherent integration. The antenna is shown in Fig. 9. The main reflector is a cylindrical parabola which is fed with an eight horn feed. Each of the eight horn elements has its own quadrature receiver and two analog–to–digital converters(ADCs) one for the in–phase and the other for the quadrature phase video signals. The antenna with its multiple receiver channels comprises a "sampled–aperture antenna" which can be processed with array signal processing algorithms.

The location of the experiment is illustrated in Fig. 10 which shows a map of Sylt. The experimental set–up is illustrated in Fig. 11. The targets were corner reflectors mounted on two poles, P_1 at a distance of 4.3 km and P_2 at a distance of 9.6 km. In this paper only results from P_2 will be presented. Variation in target height was caused by the tide. Recordings of data from each of the eight receiver channels were carried out intermittently over a period of a month. Only radar returns from the target radar range cell were recorded. All coherent integration was carried out as part of the computerized data processing. A complete description of results is found in [12]. We have selected a small group of examples to illustrate both the effect of sea state and the effect of SNR. Fig. 12 gives results using the RML algorithm for sea state SS1–SS2 while Fig. 13 gives similar results for rougher sea conditions of SS3–SS4. In Figures 12 and 13, the abscissa indicates sample number. An estimate of target height is formed at each sample number based on eight coherently integrated data vectors at 8.6 GHZ and eight at 9.6 GHz. In each receiver channel, the digitized in–phase and quadrature video comprises the real and imaginary parts of the coherent radar return. A coherently integrated data vector having eight complex components is obtained by integrating up to 512 radar returns from the target in each of the eight receiver channels. The results for variable SNR in Figures 12 and 13 were obtained by varying the amount of coherent integration. The results of Figures 12a and 13a correspond to the coherent integration of 512 radar returns for each of the eight data vectors for each of the two frequencies. For Figures 12b and 13b, the number of coherently integrated returns are 64 and 16, respectively. Figures 12c and 13c both correspond to coherent integration of 4 radar returns.

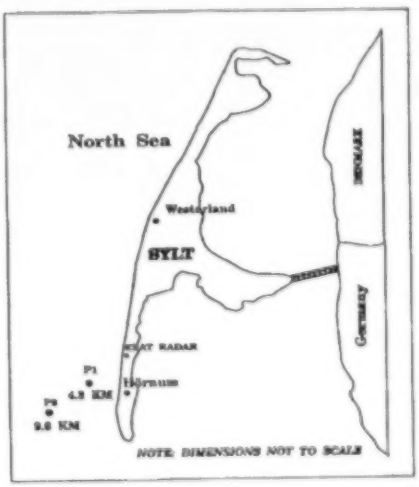

Figure 10 Map of Sylt measurement site

When the SNR is high as in Figures 12a and 13a, the RML algorithm provides excellent accuracy with a very small bias: in Fig.12a the true target height is 6.5m while the

P148278.PDF [Page: 8 of 10]

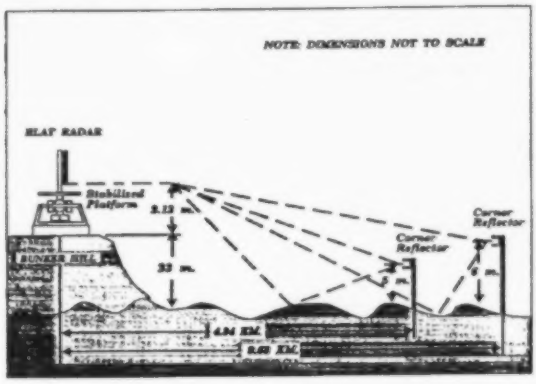

Figure 11 Geometry of Sylt Experimental site

estimated height varies between 7 and 8 m; in Fig.13a the true height is 5.7m while the estimate is near 7m. As the SNR decreases, two effects occur: the peaks of the likelihood function are displaced and the algorithm sometimes chooses the wrong peak. It is evident that the most serious effect is the selection of the wrong ambiguous peak of the likelihood function. For this reason, in the (b) and (c) curves of Figures 12 and 13, the percentage of times that the correct peak is selected is indicated. For the SS1–SS2 results, the correct peak is selected 95% of the time with an SNR of 27 dB, while for the rougher sea conditions SS3–SS4, the correct peak is selected 94% of the time. These SNR values are evaluated at the array element level and are therefore quite high for initial detection of incoming targets. However, once the radar starts to track an approaching target, the SNR should rapidly build up to a high level. The performance shown in Figures 12 and 13 is significantly better than in [12]. This is attributed to a better calibration for antenna tilt angle. [12] uses a tilt angle correction of 0.4 degrees that provides the best performance averaged over the entire data set for the entire trial period; in contrast, the tilt correction used here (0.44 degrees) is optimized for the specific data sets used to obtain the results of Figures 12 and 13. The determination of the tilt correction was formulated as a maximum likelihood problem; the correlation function as illustrated in Figure 8 was

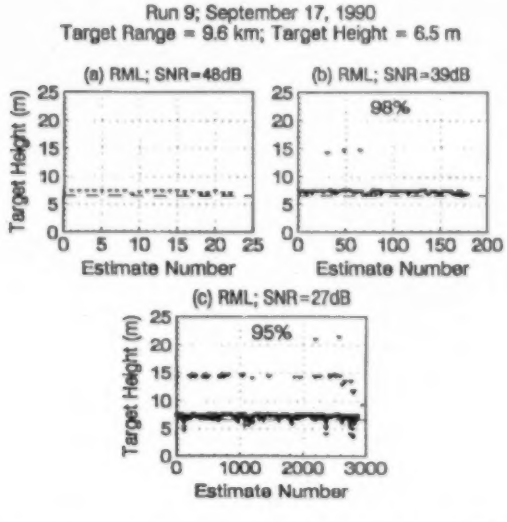

Figure 12 Performance of RML as function of SNR for sea states SS1 – SS2.

repeatedly calculated with different tilt angle corrections until the correction was found that gave the maximum correlation (peak closest to unity).

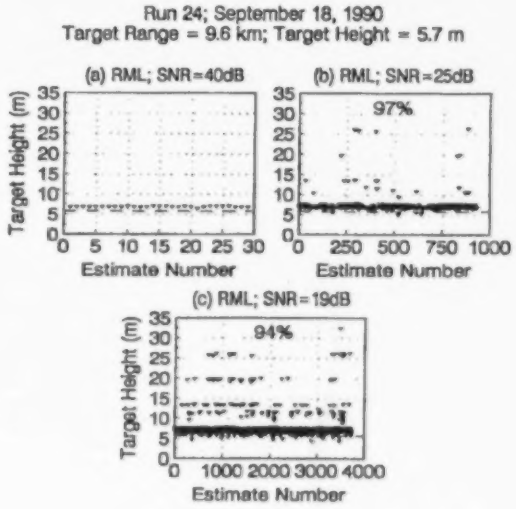

Figure 13 Performance of RML as function of SNR for sea states SS3 – SS4.

6. The Lake Huron Experiments

The Lake Huron experiments used a very wide band beacon system covering 8.05 to 12.34 GHz. This probably exceeds the bandwidth performance achievable with present–day X–band solid state radar systems. The experimental data obtained from this system and processed with the RML algorithm gives a good indication of how tracking accuracy might be improved with such a wide agile frequency band.

Fig.14 shows the experimental setup at Lake Huron. The cw beacon signal acts as a target simulator and can be synthesized to produce up to 145 frequencies within the system bandwidth. However, only 17 frequencies were used in the experimental trials. The receiving antenna

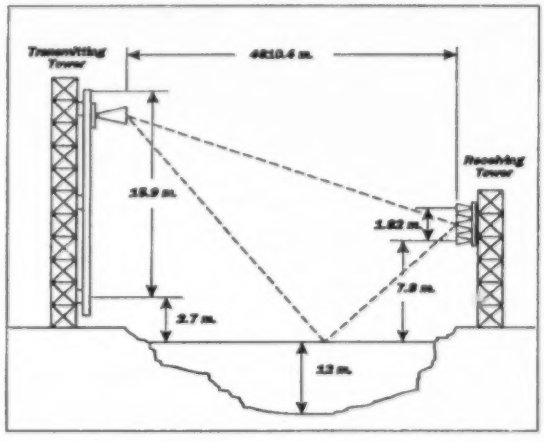

Figure 14 Experimental set–up for wideband beacon experiment – Lake Huron

P148278.PDF [Page: 9 of 10]

array has 32 10–dB horizontally–polarized horn elements. Each element has its own receiver producing in–phase and quadrature video digitized to 12–bit precision. A data acquisition system was used to collect the experimental data and transfer it to floppy disk and tape storage. The 32–element linear array had a vertical aperture of 1.82m. A very extensive description of the experimental equipment and analysis of the experimental results are found in [13].

Results of the trials will be used to demonstrate two results: the very good performance that can be achieved by using RML with a very wideband agile system; and the effectiveness achievable in applying RML to a two–element monopulse configuration when the agile bandwidth is very wide. The two–element monopulse configuration is simulated by summing the outputs of the top 16 elements to produce an upper subarray while the bottom 16 are summed to produce a lower subarray. RML applied to these two subarrays is designated RMONO while the designation RML is reserved for application of the algorithm to the total 32 elements. As well, ordinary phase monopulse with averaging over the group of selected frequencies is applied to two subarrays to provide a comparison with both RMONO and RML.

Fig 15 illustrates the performance achieved with a target height of 18.6m at a range of 4.6 km with five frequencies spread over a 2 GHz bandwidth. Both RMONO and RML gave good performance with height estimation errors of about 10m compared with phase monopulse which had an error varying between 60m and 40m. In Fig. 16 we have five frequencies distributed over a 4 GHz bandwidth. In this case, the errors for both RML and RMONO are negligibly small. In comparison, phase monopulse has an error of 30 to 40m which is significantly reduced by expanding the bandwidth from 2 to 4 GHz but still much larger than achievable with RML and RMONO.

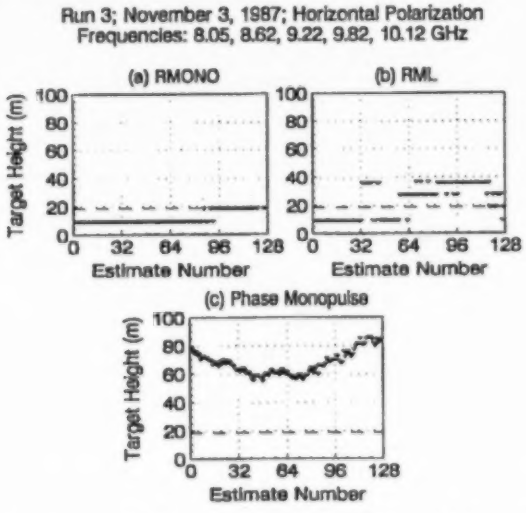

Figure 15 Performance comparison using five frequencies over a 2 GHz bandwidth.

In Figures 15 and 16 there is not much difference between RMONO and RML. This is attributed to the high signal levels and good calibration of the array. In general RML applied to all 32 elements should give better results than RMONO applied to two subarrays.

7. Conclusions

In this paper we have evaluated a number of possibilities for improved performance of naval tracking radars for low elevation targets in multipath. We have shown that frequency agility provides a powerful tool for reducing

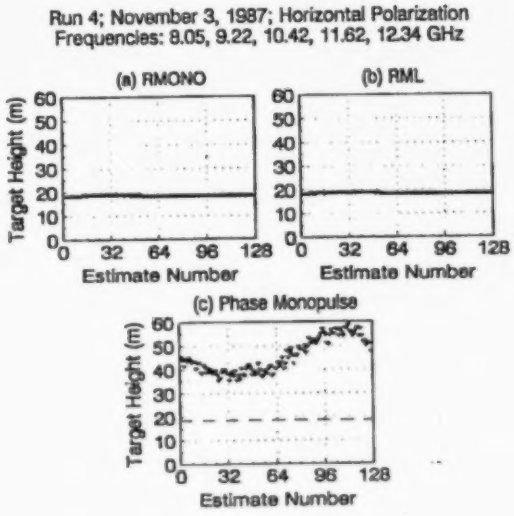

Figure 16 Performance comparison using five frequencies over a 4 GHz bandwidth.

multipath errors. Provided the frequency agile bandwidth is sufficiently wide, simple averaging of monopulse position estimates produces a good improvement – weighting the averaging according to the SNR provides an even greater improvement. In a practical system it is necessary to determine whether the degree of frequency agility is commensurate with the accuracy required for the specific weapon system. For example, semi–active missile systems require less accuracy than command–guidance systems or gun systems. Where the required accuracy is higher than achievable with monopulse, near–optimum algorithms based on the Refined Maximum Likelihood (RML) technique can provide much greater precision. The paper has presented results from two experimental trials which provided experimental verification of the effective functioning of the RML technique. The results of the Sylt experiment showed that RML could produce very good results under conditions typical of many radar systems operating in sea clutter with a moderate degree of frequency diversity . The wide–band beacon data from the Lake Huron experiment was used to show that provided the agile bandwidth was wide enough, RML can be applied to the the two outputs of a phase monopulse system (called RMONO) to give effective angle estimation, the lack of elements in the array being compensated by the wide range of frequencies.

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P148278.PDF [Page: 10 of 10]

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